

# On Excited States of Deuteron Nucleus

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For a long time it was known that deuteron, as a weakly coupled nucleon pair, has no excited states. However, A.M. Baldin et al, commenting results of the first physical experiment with accelerated nuclei at JINR synchrophasotron, assumed as far back as in 1979 that one of peaks in a differential cross-section may arise due to an "excited state of deuterium". We have established that one of the peaks in the cross-section may be explained indeed in this way and corresponds to the dibaryon reported by WASA-at-COSY Collaboration. Another peak in the same region is interpreted most likely by interference of several  $N^*$ -resonances, and this possibility was also mentioned in the paper by A.M. Baldin et al. Further experimental studies based on modern experimental facilities and more abundant statistics are necessary to verify these observations.

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## I. INTRODUCTION

Recently a proposal of QCD investigation at high density and low temperature, complementary to the heavy nuclear collisions, was suggested<sup>1,2</sup>. The proposal is based on the fact that a large number of nucleons in the interaction region is not necessary for the phase transition to occur, and only a change of the vacuum state should be initiated by some experimental environment. In particular, observation of multi-baryons (MB) may be a direct evidence of phase transitions in small nucleon systems. Separation of a MB mass from the secondary particle background is feasible if the MB decay width is narrow enough. That requires the excitation energy of MB produced should be low. For this purpose, it is reasonable to select only those experimental events in which the MB creation is accompanied with a high momentum particle, taking away an essential part of the energy from the interaction region – method of cumulative particle<sup>2</sup>. In this paper, we focus on a verification of this concept by the use of older experimental data taken at JINR synchrophasotron.

An experiment<sup>3</sup> was designed for measurement of cross-sections of pp-, ND-, and DD-interactions at 8.9 GeV momentum of primary protons and deuterons. A model of the detector operation was briefly described in<sup>3</sup>. Its parameters were established by means of measuring differential elastic cross-sections for proton-proton scattering in a known kinematic region. Three peaks were observed in the spectrum of the missing masses of the reaction  $D+D \rightarrow M_X + D$  at  $t = -0.495 \text{ GeV}^2$ . Here we shall concentrate only on one of them, called the third peak in the original paper. In regard to the third peak, M.A. Baldin et al suggested that it might occur due to: a contribution of an excited state of deuteron; scattering of a constituent quark (entering into the composition of the incident deuteron) by target deuteron; and,

in addition,  $N^*$ -baryon production. Experimental findings occurred after the paper<sup>3</sup> was written give a cause for re-examination of the suggestions mentioned above.

The present paper might be considered as a particular proposal for experimental search of phase transitions in small nucleon systems.

## II. CONSTITUENT QUARK SCATTERING

Elastic scattering of a constituent quark by the target deuteron may be considered in the framework of a model in which values of momentum and mass of the projectile quark are considered in the form

$$P_q = xP_1, \quad M_q = xM_D,$$

where  $x$  is determined from kinematics of the reaction. A necessary relation between quark mass and known experimental parameters can be found as follows. Let us denote by  $1+2 \rightarrow 3+4$  a reaction at issue, where the projectile, target and registered particles are designated by 1, 2 and 4, correspondingly, and 3 denotes an object X which mass should be determined. Two different expressions for the Lorentz invariant Mandelstam variable  $u$ ,  $u = (p_1 - p_4)^2$  and  $u = (p_2 - p_3)^2$ , where  $p_i = (E_i, \mathbf{P}_i)$ , allow to connect  $M_X$  and  $\cos \theta$  which describes the escape direction of the particle 4 in the laboratory system. A value energy of particle 4 as function of  $M_2$ ,  $M_4$  and  $t$  may be found by making use of a relation  $t = (p_2 - p_4)^2$ . In addition,  $E_3 = E_1 + E_2 - E_4$ . Proceeding on this way, one obtains

$$M_q = \frac{-M_D^2 t}{E_1 t + |\mathbf{P}_1| \sqrt{t(-4M_D^2 + t)} \cos \theta},$$

and  $M_q = 0.351 \text{ GeV}$  for  $\cos \theta = 0.396$ . This number contradicts manifestly to estimations of modern quark

TABLE I: Spin, parity and width of  $N^*$  included in our PWA. The data are given by Particle Data Group<sup>6</sup>.

$N^*$	$S_{N^*}$	$P_{N^*}$	$\Gamma_{N^*}$ , MeV
N(1440)	1/2	1	300
N(1520)	3/2	-1	115
N(1535)	1/2	-1	150

models: see, e.g.,<sup>4</sup> where  $M_q = 0.318$  GeV. On the other hand, we shall see below that a peak at  $\cos\theta = 0.396$  corresponds remarkably to the dibaryon found by WASA-at-COSY Collaboration<sup>5</sup>.

### III. PARTIAL-WAVE ANALYSIS (PWA) AND $SU(6) \otimes O(3)$ QUARK SPECTROSCOPY

Now let us turn to study of a possible contribution of  $N + D \rightarrow N^* + D$  reactions to the experimental cross-section. Isotopic spin conservation constrains isospin of  $N^*$  to be equal to 1/2. Therefore,  $\Delta$ -baryon excitations of nucleon may be ignored here, and among  $N^*$  excitations only N(1440), N(1520) and N(1535) are important in the kinematic region under consideration. Main characteristics of the baryon resonances taken into account are shown in Table I.

Besides the spatial parity,  $\hat{P}$ , conservation, one should respect the angular momentum,  $\hat{\mathbf{J}} = \hat{\mathbf{L}} + \hat{\mathbf{S}}$ , preservation. In  $sp$ -approximation, appropriate to the hard collisions, only  $L = 0$  and  $L = 1$  eigenvalues of the orbital momentum can be considered. In these terms, parities of initial and final states may be expressed as follows:

$$P_i = P_N P_D (-1)^{L_i} = (-1)^{L_i} = P_f = P_{N^*} (-1)^{L_f}. \quad (1)$$

Further PWA may be simplified essentially via application of the  $SU(6) \otimes O(3)$  description of baryon excitations, suggested by R.H. Dalitz and co-authors<sup>7</sup>. According to it, spin  $\mathbf{S}_{N^*}$  of a nucleon resonance  $N^*$  may be represented as follows:

$$\mathbf{S}_{N^*} = \mathbf{S}_N + \mathbf{l}, \quad (2)$$

where  $\mathbf{S}_N$  is spin of the unexcited nucleon  $N$  and  $\mathbf{l}$  is orbital momentum of quarks inside of the excited nucleon  $N^*$ . Using (1), it is readily seen that for each partial wave, which is characterized by fixed values of  $J$  and  $P$ , a value of parity  $P_{N^*}$  of nucleon resonance  $N^*$  determines totally a possible behavior of  $l$  and  $L$  values. For N(1440), one has  $P_{N^*} = P_N = 1$  which implies  $l = 0$ , and, subject to (1), also  $L_f = L_i$ . For N(1520) and N(1535),  $P_{N^*} = -1$ ; therefore  $l = 1$ . According to (2) and Table I, we can interpret spins of N(1520) and N(1535) as two different manners of summation, using Clebsch-Gordan coefficients, of quark orbital momentum  $l = 1$  and initial spin  $S_N = 1/2$  of unexcited nucleon. The

parity conservation leads to simultaneous change of  $L$  and  $l$  values in two possible ways:

$$L_i = 1 \rightarrow L_f = 0, \quad l_i = 0 \rightarrow l_f = 1, \quad (3)$$

and

$$L_i = 0 \rightarrow L_f = 1, \quad l_i = 0 \rightarrow l_f = 1. \quad (4)$$

In the frame of  $SU(6) \otimes O(3)$  spectroscopy, these cases correspond to conservation of eigenvalues of operator  $\mathbf{M}^2 = (\mathbf{L} + \mathbf{l})^2$ , which are equal to 2 and 0, accordingly. Operator of the total orbital momentum  $\mathbf{M}$  commutes with  $\mathbf{M}^2$ , and we can develop a more detail picture including account of a direction of  $\mathbf{M}$ . Below we shall consider centrally symmetric interaction conserving the direction of  $\mathbf{M}$ . In this case, conservation of the total angular and orbital momenta implies preservation of the total spin,  $\mathbf{S} = \mathbf{J} - \mathbf{M}$ , of the system and our description admits a further development.

A general expression of the  $N + D \rightarrow N^* + D$  amplitude linear relative to  $S_N$ ,  $S_D$  and invariant under time reversal and space rotation or reflection is as follows<sup>8</sup>

$$T(\mathbf{S}_N, \mathbf{S}_D) = C_1 + C_2(\mathbf{S}_N + \mathbf{S}_D) \cdot \mathbf{j} + C_3(\mathbf{S}_N - \mathbf{S}_D) \cdot \mathbf{j} \quad (5) \\ + C_4(\mathbf{S}_N \cdot \mathbf{j})(\mathbf{S}_D \cdot \mathbf{j}) + C_5(\mathbf{S}_N \cdot \mathbf{k})(\mathbf{S}_D \cdot \mathbf{k}) + C_6(\mathbf{S}_N \cdot \mathbf{i})(\mathbf{S}_D \cdot \mathbf{i}),$$

where

$$\mathbf{j} = \frac{\mathbf{p} \times \mathbf{p}'}{|\mathbf{p} \times \mathbf{p}'|}, \quad \mathbf{k} = \frac{\mathbf{p} - \mathbf{p}'}{|\mathbf{p} - \mathbf{p}'|}, \quad \mathbf{i} = \frac{\mathbf{p} + \mathbf{p}'}{|\mathbf{p} + \mathbf{p}'|},$$

$\mathbf{p}$  and  $\mathbf{p}'$  are momenta of the ingoing nucleon and outgoing  $N^*$ . Here  $C_i$  are scalar functions which may depend only on a scalar  $(\mathbf{p} \cdot \mathbf{p}')/|\mathbf{p}||\mathbf{p}'|$  which is in one-to-one correspondence with  $\cos\theta$ . In fact, we should claim  $C_3 = 0$ , for  $\mathbf{S}_N - \mathbf{S}_D$  does not commute with  $(\mathbf{S}_N + \mathbf{S}_D)^2$  and the corresponding term breaks conservation of an absolute value of the total spin. Similarly, it is possible to show that  $C_4 = C_5 = C_6 = 0$ <sup>26</sup>. Because of the total spin conservation, a term proportional to  $(\mathbf{S}_N + \mathbf{S}_D)^2$  is not included in (5) as far as it is proportional to unit operator for any state with a total spin  $S$  fixed (where, as usual,  $\mathbf{S}^2 = S(S+1)$ ). Efficiently, it is included in  $C_1$ .

Thus, we have seen that the parity conservation admits concordant alteration of  $L$  and  $l$  according to (3) and (4). From the physical point of view (3) corresponds to swapping external orbital momentum of  $N+D$  system into nucleon, and (4) corresponds to excitation of the both external,  $\mathbf{L}$ , and intranucleonic,  $\mathbf{l}$ , momenta. These processes may be described by a nonlocal operator  $(\mathbf{R} \cdot \mathbf{r})$  included in the interaction amplitude. Here  $\mathbf{R}$  is a polar vector given in the laboratory system, which is directed at center of inertia of  $N+D$  system, and  $\mathbf{r}$  is a polar vector pointed at center of mass of the nucleon colliding with deuteron. Without loss of generality, we may also suggest  $(\mathbf{R} \cdot \mathbf{R}) = (\mathbf{r} \cdot \mathbf{r}) = 1$ . Then  $T$ -matrix describing

production of baryon from Table I may be written in the form

$$T(N + D \rightarrow N^* + D) = A + B(\mathbf{S}_N + \mathbf{S}_D) \cdot \mathbf{j} \\ + (\mathbf{R} \cdot \mathbf{r}) [C + D(\mathbf{S}_N + \mathbf{S}_D) \cdot \mathbf{j}]. \quad (6)$$

Here  $A$  and  $B$  describe spin independent and spin dependent parts of interaction corresponding to  $N(1440)$  production. Similarly,  $C$  and  $D$  describe interaction corresponding to  $N(1520)$  and  $N(1535)$ . Using an identity

$$(\mathbf{R} \cdot \mathbf{r}) = \frac{1}{2} (R_+ r_- + R_- r_+) + R_z r_z$$

and well-known formulae for  $\mathbf{R}$  and  $\mathbf{r}$  operators<sup>8</sup>

$$\langle L = 1, M = 0 | R_z | L = 0, M = 0 \rangle = -i/\sqrt{3},$$

$$\langle l = 1, m = 0 | r_z | l = 0, m = 0 \rangle = -i/\sqrt{3},$$

$$\langle L = 1, M = -1 | R_- | L = 0, M = 0 \rangle = -i\sqrt{2/3},$$

$$\langle l = 1, m = +1 | r_+ | l = 0, m = 0 \rangle = +i\sqrt{2/3},$$

it is possible to find that amplitudes of the processes (3) and (4) are equal to 1 and  $1/3$ , accordingly.

#### IV. OBSERVABLE PARTICLES, CROSS-SECTION

In fact, baryon resonances  $N(1440)$ ,  $N(1520)$  and  $N(1535)$  were not observed directly. They were present in an intermediate state and may be identified only via their decay products. Therefore interference terms corresponding simultaneous propagation of matter through several quantum states with different spins and parities should be taken into account. We take for granted that possible final states tolerating macroscopic recognition may contain  $N\pi$ ,  $N\pi\pi$  and  $N\eta$ , of course, besides deuteron. For  $N(1440)$  and  $N(1520)$ , corresponding decay probabilities can be estimated as  $w_{1\pi} \approx 0.65$ ,  $w_{2\pi} \approx 0.35$ ,  $w_\eta \approx 0$ ; and  $w_{1\pi} \approx 0.5$ ,  $w_{2\pi} \approx 0.1$ ,  $w_\eta \approx 0.4$  for  $N(1535)$ , see<sup>6</sup>.

Baryon resonances leave imprint of their existence only as propagators in total amplitude. For example, a transition  $N+D \rightarrow N+\pi+D$  is described by the following  $T$ -matrix:

$$T(N + D \rightarrow N + \pi + D) =$$

$$\frac{(A + B(\mathbf{S}_N + \mathbf{S}_D) \cdot \mathbf{j})T(N(1440) \rightarrow N + \pi)}{M_{N(1440)}^2 - M_X^2 - iM_{N(1440)}\Gamma_{N(1440)}}$$

$$+ \frac{f(S, 3/2) (C + D(\mathbf{S}_N + \mathbf{S}_D) \cdot \mathbf{j}) T(N(1520) \rightarrow N + \pi)}{M_{N(1520)}^2 - M_X^2 - iM_{N(1520)}\Gamma_{N(1520)}} \quad (7)$$

$$+ \frac{f(S, 1/2) (C + D(\mathbf{S}_N + \mathbf{S}_D) \cdot \mathbf{j}) T(N(1535) \rightarrow N + \pi)}{M_{N(1535)}^2 - M_X^2 - iM_{N(1535)}\Gamma_{N(1535)}}.$$

Analogous expressions take place for  $N+D \rightarrow N+\pi+\pi+D$  and  $N+D \rightarrow N+\eta+D$  transitions. In (7), scalar functions  $A$ ,  $B$ ,  $C$ ,  $D$  are the same as in (6), and factors  $f(S, N^*)$  may be found on basis of Clebsch-Gordan coefficients, as it was mentioned in previous section. Following this prescription, one can find

$$f(S, S_{N^*}) = \sum_{\sigma_1=\pm 1/2} \sum_{\sigma_2=0,\pm 1} \sum_{m=0,\pm 1}$$

$$\left\langle \frac{1}{2} \sigma_1 1 \sigma_2 \left| S, \sigma_1 + \sigma_2 \right. \right\rangle \left\langle \frac{1}{2} \sigma_1 1 m \left| S_{N^*}, \sigma_1 + m \right. \right\rangle,$$

and

$$f\left(\frac{1}{2}, \frac{1}{2}\right) = 2 + \sqrt{2}, \quad f\left(\frac{3}{2}, \frac{1}{2}\right) = \frac{2}{3},$$

$$f\left(\frac{1}{2}, \frac{3}{2}\right) = 0, \quad f\left(\frac{3}{2}, \frac{3}{2}\right) = \frac{4}{3} (\sqrt{2} + \sqrt{3} + \sqrt{6}),$$

where we adopted notations of the Clebsch-Gordan coefficients from<sup>8</sup>.

Here we should re-arrange a usual formula for cross-section<sup>9</sup>,

$$\frac{d^2\sigma}{dt dM_X^2} = \frac{\pi}{\lambda^{1/2}(s, m_N^2, m_d^2)} \frac{1}{(2S_N + 1)(2S_D + 1)} \\ \times \sum_{M_i, M_f} \int d\text{Lips}(M_X^2, \text{decay products}) |T_{M_i M_f}|^2, \quad (8)$$

where  $M_i$  and  $M_f$  are spin projections of particles in initial and final states, into terms of our model of the orbital nucleon excitations. To this end, we replace averaging over  $M_i$  and summation over  $M_f$  by corresponding operation over  $\Sigma_i$  and  $\Sigma_f$ , which are total spin projections of *quarks* in initial and final states. For nonpolarized initial states, probabilities of occurrence of  $S = 1/2$  and  $S = 3/2$  are equal to  $1/3$  and  $2/3$ , accordingly. Taking into account that the contribution of orbital excitations is already included by means of  $f(S, S_{N^*})$ , we may write:

$$\frac{1}{(2S_N + 1)(2S_D + 1)} \sum_{M_i, M_f} |T_{M_i M_f}|^2 \\ = \frac{1}{3} \sum_{\Sigma_f=\pm 1/2} |\overline{T_{\Sigma_i \Sigma_f}}|^2 + \frac{2}{3} \sum_{\Sigma_f=\pm 1/2, \pm 3/2} |\overline{T_{\Sigma_i \Sigma_f}}|^2,$$

and then transform

$$\begin{aligned}\sum_{\Sigma_f} \overline{|T_{\Sigma_i \Sigma_f}|^2} &= \sum_{\Sigma_f} \overline{T_{\Sigma_i \Sigma_f} T_{\Sigma_i \Sigma_f}^*} = \sum_{\Sigma_f} \overline{T_{\Sigma_i \Sigma_f} T_{\Sigma_f \Sigma_i}^\dagger} \\ &= \overline{(TT^\dagger)_{\Sigma_i \Sigma_i}} \equiv \frac{1}{2S+1} \text{Tr}(TT^\dagger).\end{aligned}$$

Now it is easy to prove a relation

$$\begin{aligned}\frac{1}{(2S_N+1)(2S_D+1)} \sum_{M_i, M_f} |T_{M_i M_f}|^2 \\ = \frac{1}{6} \sum_{S=\frac{1}{2}, \frac{3}{2}} \text{Tr}(T(S)T(S)^\dagger),\end{aligned}$$

which means that values of total spin  $S = 1/2$  and  $3/2$ , as well as all its projections  $\Sigma = \pm 1/2$  and  $\Sigma = \pm 1/2, \pm 3/2$ , correspondingly, give equal contribution to the final result. It should be stressed that the sign  $^\dagger$  of Hermitian conjugation refers to  $T$  as to spin operator, and it does not mean transposition of other variables<sup>27</sup>.

Calculations of  $\text{Tr}(TT^\dagger)$  may be completed with making use of relations:  $\text{Tr}(\mathbf{S} \cdot \mathbf{j}) = 0$ ,

$$\text{Tr}(1) = \begin{cases} 2, & S = 1/2, \\ 4, & S = 3/2, \end{cases} \quad \text{Tr}(\mathbf{S} \cdot \mathbf{j})^2 = \begin{cases} 1/2, & S = 1/2, \\ 5, & S = 3/2. \end{cases}$$

Absolute values of the decay amplitudes are fixed in terms of decay widths<sup>9</sup>,

$$\Gamma_{N^*, f} = \frac{1}{2M_{N^*}} \int d\text{Lips}(M_X^2, f) \sum_{M_f} |T(N^* \rightarrow f)|^2,$$

where subscript  $N^*$  denotes a particular baryon resonance,  $f$  is its decay products. We confine our estimations of interference between different baryon resonances to operations with phase space averaged values. For this purpose, we define<sup>28</sup>

$$\Gamma_{N^*, f} = \frac{(2S_{N^*}+1)}{2M_{N^*}} \overline{|T(N^* \rightarrow f)|^2} \text{Lips}(M_X^2, f),$$

and substitute<sup>29</sup>

$$\begin{aligned}(2S_{N^*}+1) \left( \overline{|T(N_i^* \rightarrow f)|^2} \right)^{1/2} \left( \overline{|T(N_j^* \rightarrow f)|^2} \right)^{1/2} \\ \times e^{i(\bar{\alpha}_i - \bar{\alpha}_j)} \text{Lips}(M_X^2, f) = 2\sqrt{M_i M_j \Gamma_i \Gamma_j} e^{i(\bar{\alpha}_i - \bar{\alpha}_j)} \quad (9)\end{aligned}$$

for

$$\int d\text{Lips}(M_X^2, f) \sum_{M_f} T(N_i^* \rightarrow f) T^*(N_j^* \rightarrow f)$$

if  $M_X$  is greater than  $N^*$  decay threshold and zero otherwise. Here baryon resonances are different,  $i \neq j$ , and

decay particles are the same for the both multipliers under integral sign.

Strictly speaking, separate control of spin projections of  $N^*$  is not kept in mind in our description, but only projection of total spin of quarks in the final state of reaction  $N+D \rightarrow N^*+D$ . Therefore we should take into account availability of deuteron too and replace  $M_f$  with  $\Sigma_f$  and  $S_{N^*}$  with  $S$  in the previous formulae. Such a treatment may be understood as summation over quark spin projections inside  $N^*$  and spectator deuteron. Contribution of orbital excitations into spin projection of  $N^*$  is already included explicitly by means of  $f(S, S_{N^*})$ , as it was mentioned above. This new interpretation of spin summation rule is an inevitable corollary of consideration of baryon as a compound system with its own inner structure.

In the accepted approximation, only phases of the decay amplitudes  $\bar{\alpha}_i$  may be used as adjustable parameters for experimental data matching. In addition, eight real numbers corresponding complex parameters  $A, B, C, D$  in (7) are brought into play for this purpose. Interference terms corresponding decays of  $N^*$  via  $\eta$  are absent since cross-sections of this channel are negligible quantities but for one of the resonances under consideration (see values  $w_\eta$  in beginning of this section). The final formula describing the experimental data may be written in the following form:

$$\begin{aligned}\frac{d^2\sigma}{dt dM_X^2} &= \frac{\pi}{6\lambda^{1/2}(s, m_N^2, m_d^2)} \\ &\times \sum_{f, S} \int d\text{Lips}(M_X^2, f) \text{Tr}(T(S, f) T^\dagger(S, f)) + E,\end{aligned}$$

where  $f = N\pi, N\eta, N\pi\pi$ ,  $S = \frac{1}{2}, \frac{3}{2}$  and additional adjustable parameter  $E$  describes a contribution of direct pion production near  $M_X^2 = 1.5 \div 2 \text{ GeV}^2$ .

## V. SOME DETAILS OF NUMERICAL CALCULATIONS

To reach an optimum in describing the experimental data we minimized total deviation square for 22 experimental points from the theoretical curve. Ten central experimental points, as the most important, were taken with unit weights and six ones on their left and six ones on their right were scaled with 0.5 significance. MAPLE procedure NLPSolve for the local minimum search was used for optimal selection of theoretical parameters. Several series, each containing 20 000 different sets of random initial values of parameters, were generated and only 30 percent of them were finished without interruption because of very big number of steps towards a local minimum. Points of the interruptions were considered as local minima too, because they usually correspond to wanderings along valleys. Then the best local minimum was

taken for each of the series, and values of objective function corresponding to them were compared. They turned out to be equal within accuracy of 11 decimal digits. All the best local optima have demonstrated that experimental data demand unambiguously:

$$|A| = 0, \quad |C| = 0. \quad (10)$$

This means that phases  $\phi_A$  and  $\phi_C$  of complex numbers  $A$  and  $C$  have no impact upon objective function. For removal of degeneration, we have fixed  $\phi_A = \phi_C = 0$  and introduced condition (10) explicitly into minimizing functional. Now the normal mode of NLPsolve performance increased up to 55 percent signalling, nevertheless, that a large degeneration still persisted. Three series of numerical experiments, containing 100, 1000 and 20 000 events, with random selections of initial values of the remaining parameters were fulfilled. They showed that parameters  $|B|$ ,  $|D|$  and  $E$  are identical in all the cases and are determined with accuracy of 4 and 6 decimal digits already in the series with 100 and 1000 events. However, all phases underwent rather strong changes with growth of statistics, signalling that minimizing functional remains degenerate with respect to them. Thus, the optimization problem does not allow us to determine phases of parameters  $A$ ,  $B$ ,  $C$ ,  $D$ ,  $T(N_i^* \rightarrow N + \pi)$  and  $T(N_i^* \rightarrow N + \pi + \pi)$ , because many of their sets describe equally well the experimental data. A grade of fidelity of reproduction of the experimental data by this model may be seen in Fig. 1.

We have also fulfilled evaluation of the model parameters using only 10 experimental points taken straight from the fine structure location, trying to enhance an impact of the most important region. It was technically fully regular procedure, as far as we had only 8 independent parameters at that stage. However, an agreement between theory and experiment has not been improved even in this case.

## VI. CONCLUSIONS AND DISCUSSION

Numerical analysis fulfilled within the bounds of our model has revealed two nonobvious properties of hard N-D and D-D scattering. First of all, it was established that experimental data<sup>3</sup> show strong spin dependence of  $N+D \rightarrow N^*+D$  transition amplitude, see (6) with  $A = C = 0$ . Secondly, comparison of the experimental data and theory shown in Fig. 1 makes an explicit hint of dibaryon production in this kinematic region. Indeed, on the one hand, consideration only usual nucleon excitations cannot explain the fine structure shown in the figure. On the other hand, assumption about presence of a dibaryon at  $M_{2B} \approx 2.38$  GeV,  $\Gamma_{2B} \approx 70$  MeV, seen by WASA-at-COSY Collaboration<sup>5</sup> allows one to explain it very naturally. Isospin conservation predicts certainly that reaction  $D+D \rightarrow \text{dibaryon} + D$  should yield dibaryon with isospin  $I = 0$ , which also corresponds to the WASA-at-COSY result<sup>5</sup>. Thus, our consideration of the data on the hard deuteron-deuteron scattering<sup>3</sup>

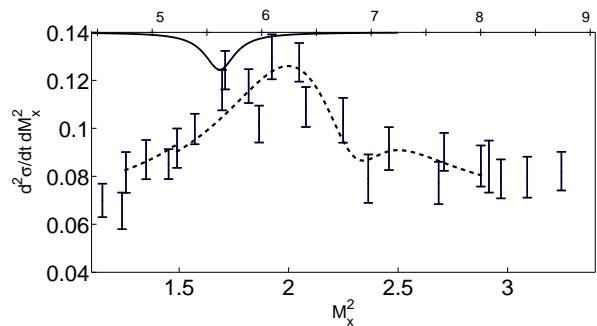


FIG. 1: The experimental data (bars) in the range of the third peak and their explanation by the sum of contributions of  $N+D \rightarrow N^*+D$  reactions (dashed line). The lower scale corresponds to the kinematics of reaction  $N+D \rightarrow N^*+D$ , the top one describes reactions  $D+D \rightarrow X+D$ , which implies the dibaryon production. A possible contribution of a dibaryon at 2.37 GeV,  $\Gamma \approx 70$  MeV reported by WASA-at-COSY Collaboration<sup>5</sup> into the cross-section is shown with the over-turned solid line.

meets the expectation to observe the transition of nucleon matter into other states using the method of cumulative particle which allows to recognize quasi-resonance peaks in the reaction cross-section.

To check our conclusions, it would be enough to measure with a good precision production cross-sections of  $N(1440)$ ,  $N(1520)$  and  $N(1535)$  from  $N+D \rightarrow N^*+D$  reactions in appropriate kinematic region, and direct production of pions therein. This allows one to take into account the background. In addition, repeating experiment<sup>3</sup> with higher accuracy is necessary too for unambiguous recognition of dibaryon by its mass and width. Theoretical and experimental study of the phases entering into expression for production amplitude is ineffectual in this respect, so long as resultant cross-section is weakly dependent on them (see previous section). Investigation of decay products of dibaryon will make it possible to identify its spin and parity and compare with  $J^P = 3^+$  observed in<sup>5</sup>.

It is interesting to review ability of the lattice QCD to say something definite about existence of dibaryons. All lattice QCD collaborations have found stable NN-dibaryons and dibaryons containing s-quarks, but quark masses in their calculations are higher than the physical values, see, e.g.,<sup>10,11</sup>. Chiral extrapolations of these results to the physical point gave, however, evidences against the existence of such dibaryons, see, e.g.,<sup>12</sup>. These calculations deal with ground states and say nothing about unstable states corresponding to a possibility of two-baryon fusion into 6-quark bag with a value of mass larger than a sum of masses of the initial baryons. Recent progress in excited baryon spectroscopy is depicted in<sup>13,14</sup>. Corresponding results based on nonphysical quark masses too cover only one-baryon states so far and are in a poor agreement with experimental N and  $\Delta$  excitation spectra. The first excited state in two-nucleon

system was found in lattice QCD in<sup>15</sup> but with a heavy quark mass corresponding to  $m_\pi = 0.8$  GeV. Therefore, predicting quasi-bound states of a multibaryon systems remains a difficult challenge in lattice QCD till now.

Another important question: what is the reason that so few signs of dibaryons currently exist in spite of their search in the network of partial-wave analysis? The most likely answer, as we see it, is still an unsatisfactory precision of PWA. Indeed, incorporating the additional data of WASA-at-COSY Collaboration into the SAID analysis produces a pole in support of the resonance hypothesis<sup>16</sup>.

A trivial generalization of the method of a cumulative particle is to select events with several,  $n > 1$ , secondary particles, not necessarily containing a cumulative one, which accompany a dibaryon production. Such a group of the additional particles, e.g., pions, may take away an excess of excitation energy, which put the main obstacle in the way of dibaryon recognition. In particular, Yu.A. Troyan reported the registration of some dibaryons using just this method<sup>17-19</sup> It should be, however, noted that most of experimental searches of dibaryons carried out in the past must be exposed to requalification. Let us consider, for example, a paper by B.M.Abramov et al<sup>20</sup>, which is cited sometimes as a convincing argument against one of Yu.A. Troyan's experiments. Even gross inspection of that paper reveals the following grave shortcomings. Firstly, no methods of a background subtraction have been used. The solid line in the main figure of the paper<sup>20</sup> is only an optimal approximation of the experimental invariant mass spectrum containing, in the general case, a sum of background and dibaryon contributions. Secondly, number of events and precision of measurements do not allow to obtain a mass spectrum resolution nearly 1 MeV, which is necessary to verify confidently the Troyan results. Thirdly, the conditions of "deep cooling", which was ensured in Troyan's experiments, has not been fulfilled in<sup>20</sup> (see<sup>21</sup> for details).

All dibaryons reported in<sup>17,18</sup> were observed in inelastic N-N interactions with additional secondary pions. The extra pions take away an excess of excitation energy – a process which is a some kind of annealing. This may reconcile two opposite requirements imposed simultaneously on the system: it must be strongly compressed to form a compound state and it must be cold enough, since highly excited levels are usually short-living and elusive. Two additional pions in final state were in WASA-at-COSY and CELSIUS/WASA Collaborations experiments<sup>5,22,23</sup>. Therefore, we may suggest with high reliability that synthesis of new multibaryons, and particularly dibaryons, should succeed an observation made also for synthesis of new transuranium elements – the system must be as much cold as possible to be observable readily.

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  - <sup>26</sup> For any vector  $\mathbf{n}$  an identity  $(\mathbf{S}_N \cdot \mathbf{n})(\mathbf{S}_D \cdot \mathbf{n}) = \frac{1}{2}((\mathbf{S} \cdot \mathbf{n})^2 - (\mathbf{S}_N \cdot \mathbf{n})^2 - (\mathbf{S}_D \cdot \mathbf{n})^2)$  holds true. The term  $(\mathbf{S}_N \cdot \mathbf{n})^2 = 1/4$  in the parentheses preserves  $\mathbf{S}$ , the term  $(\mathbf{S} \cdot \mathbf{n})^2$  commutes with  $\mathbf{S}^2$ , but does not with  $\mathbf{S}$ . This means that it conserves an absolute value of the total spin and breaks its direction. The term  $(\mathbf{S}_D \cdot \mathbf{n})^2$  does not maintain a direction of  $\mathbf{S}_D$  and therefore a direction of  $\mathbf{S} = \mathbf{S}_D + \mathbf{S}_N$  or even an absolute value of the total spin.
  - <sup>27</sup> This mathematical trick is described in<sup>8</sup> in section devoted to spin-orbit interaction.
  - <sup>28</sup> Hereafter we retain the overline as notation for averaging over Lorentz-invariant phase space.
  - <sup>29</sup> Using Cauchy-Bunyakovsky-Schwarz inequality, it may be proven that modulus of the interference terms defined by (IV) is in the general case greater than the true one. Therefore the role of interference is overestimated in our calculations. Thus, we create an optimum for explanation of experimental data by interference between different nucleon excitations, as far as the resonances have too large widths to explain cross-section by themselves.